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Sherrit et al.

(54) FLOW ENERGY HARVESTING DEVICES AND SYSTEMS

(71) Applicant: **CALIFORNIA INSTITUTE OF TECHNOLOGY**, Pasadena, CA (US)

(72) Inventors: **Stewart Sherrit**, Montrose, CA (US); **Hyeong Jae Lee**, La Canada, CA (US); **Tim Colonius**, Sierra Madre, CA (US); **Luis Phillipe Tosi**, Los Angeles, CA (US)

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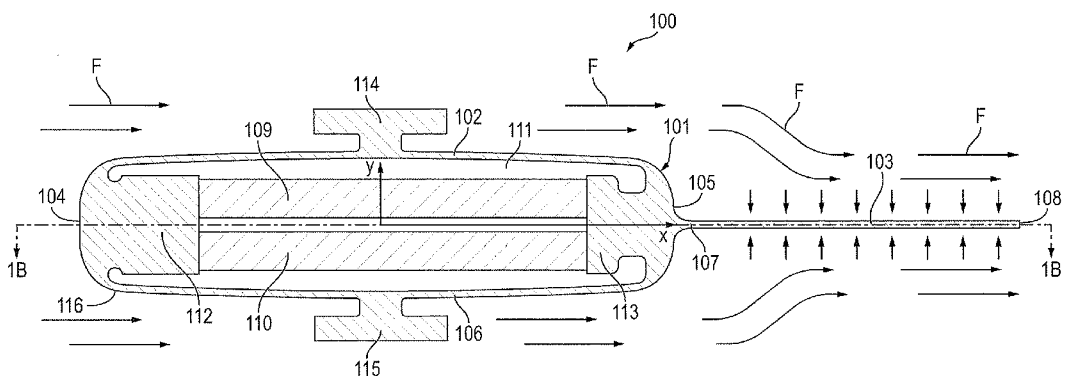
(57) **ABSTRACT**

A flow energy harvesting system including a nozzle-diffuser defining a spline-shaped flow channel and a flow energy harvesting device in the spline-shaped flow channel of the nozzle-diffuser. The spline-shaped flow channel includes a converging portion, a diverging portion, and a constriction section between the converging and diverging portions. The flow energy harvesting device includes a flextensional member having a frame and a cantilever extending outward from the frame, and a stack of piezoelectric elements housed in an interior cavity defined in the frame. The cantilever is a non-piezoelectric material. The frame of the flextensional member is in the converging portion and the cantilever is in the constriction section of the spline-shaped flow channel. The frame is configured to deform and elongate the piezoelectric elements to generate a current based on the piezoelectric effect when a fluid flows through the spline-shaped flow channel and generates unbalanced forces on the cantilever due.



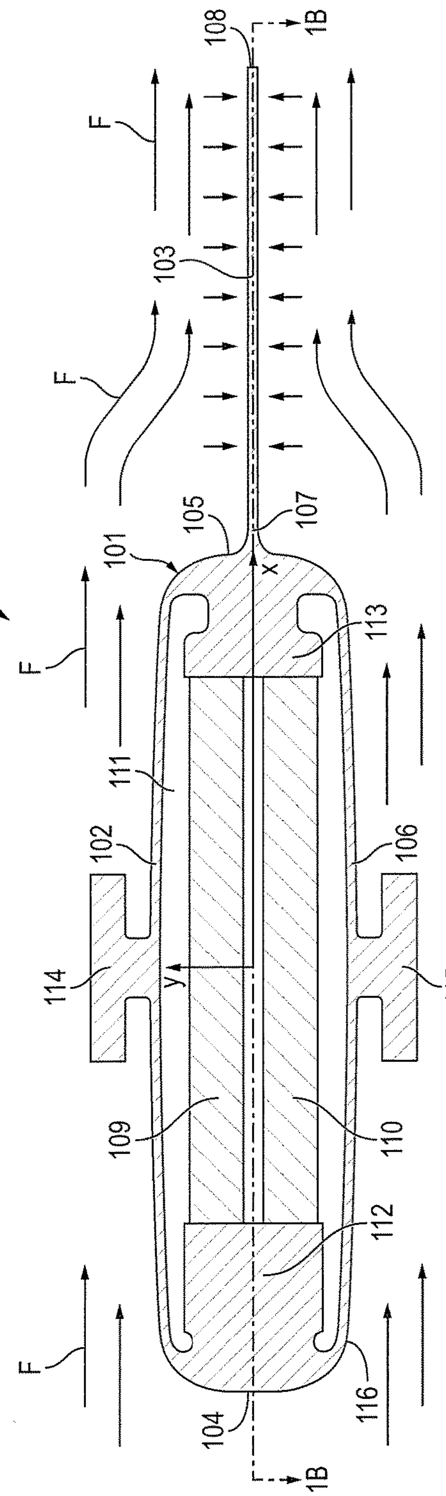

100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
F
x
y
1B

FIG. 1A

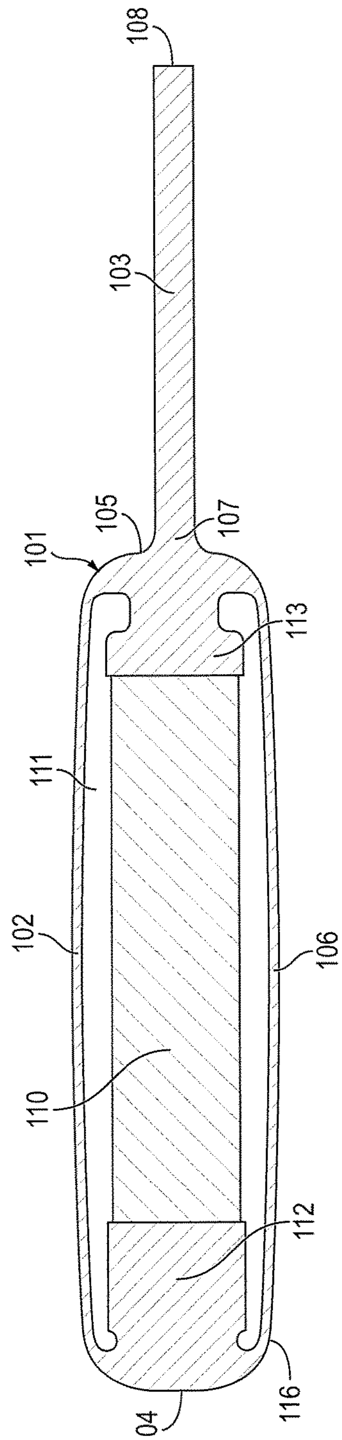

101
102
103
104
105
106
107
108
110
111
112
113
116

FIG. 1B

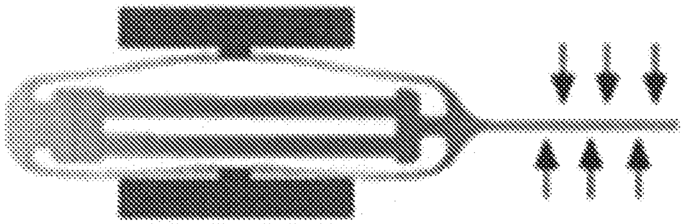


FIG. 2A

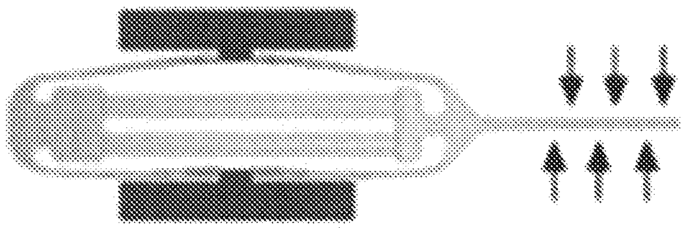


FIG. 2B

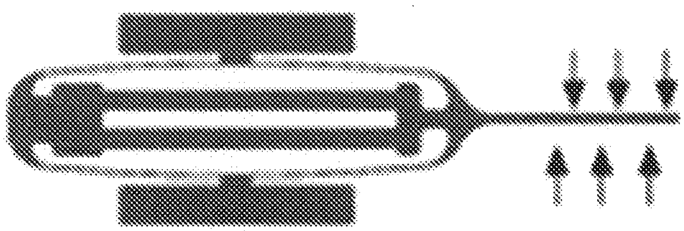


FIG. 2C

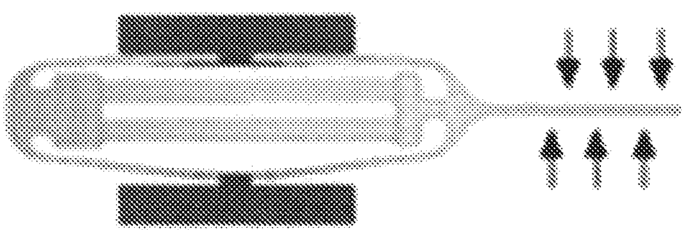


FIG. 2D

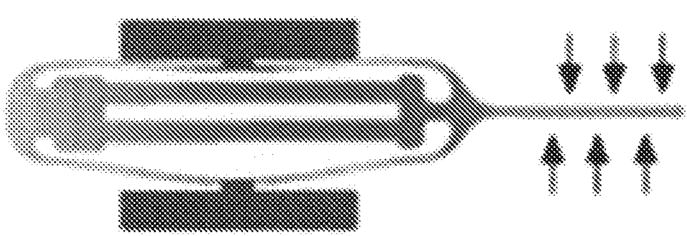


FIG. 2E

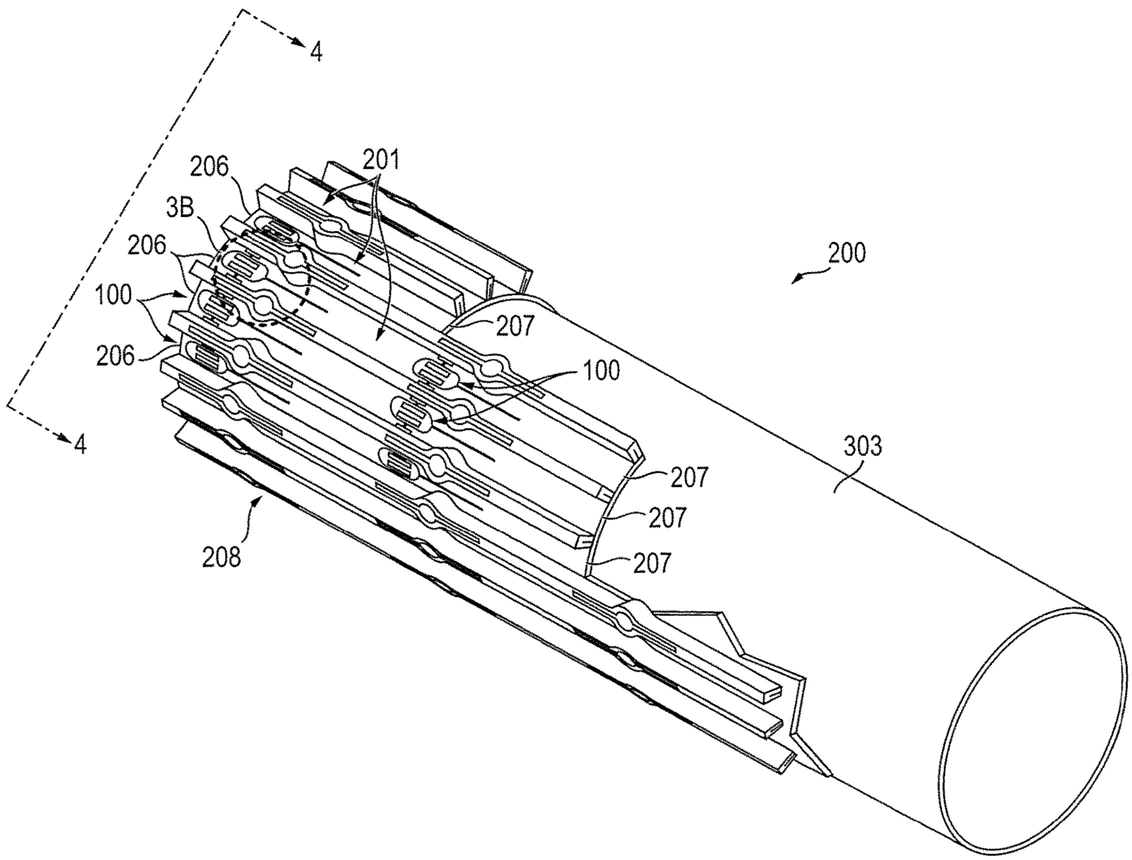

4
201
206
3B
200
206
100
207
206
100
4
303
207
207
207
208

FIG. 3A

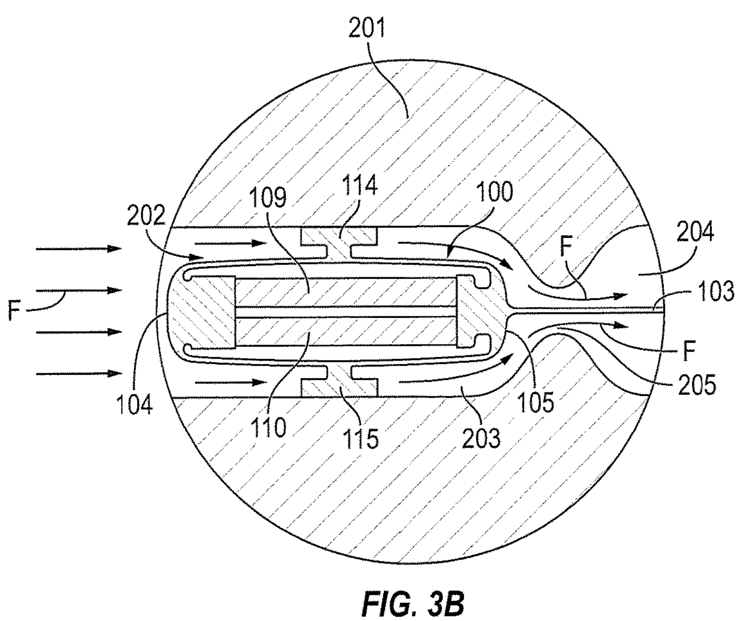

201
114
100
109
202
204
F
103
F
F
104
105
205
110
115
203

FIG. 3B

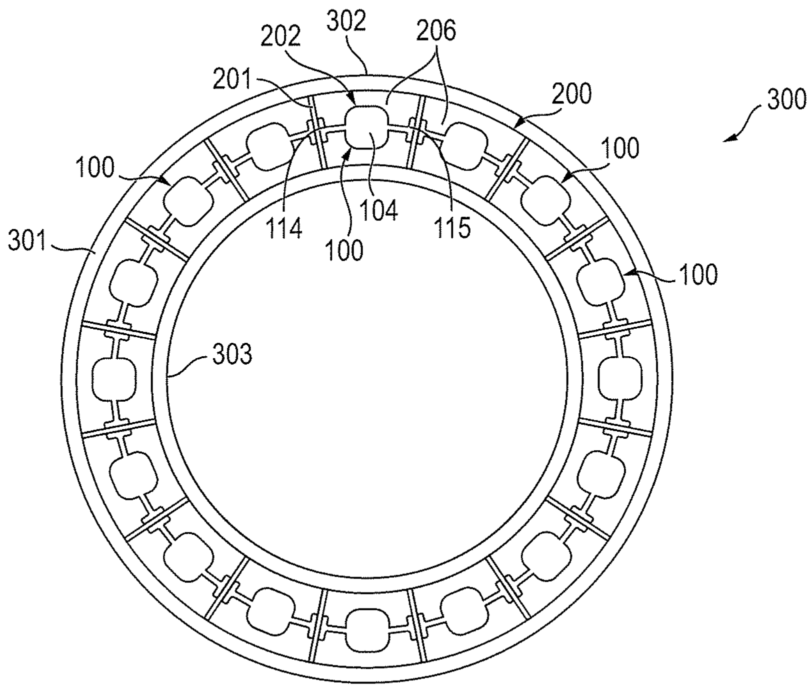


FIG. 4

FLOW ENERGY HARVESTING DEVICES AND SYSTEMS

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH/DEVELOPMENT

[0001] The invention described herein was made in the performance of work under a NASA contract NNN12AA01C, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected to retain title.

FIELD

[0002] The present disclosure relates generally to flow energy harvesting devices.

BACKGROUND

[0003] To operate electronics in remote locations, such as sensors or actuators down hole in an oil producing wellbore, power must be transmitted down the wellbore to the electronics or generated down hole in the production zone of the wellbore. However, transmitting power down the wellbore to the electronics is difficult due to the presence of various oil production equipment in the wellbore, such as production packers.

[0004] Conventional bimorph cantilever-type piezoelectric energy harvesters, which are typically used in existing vibration-induced energy harvesting devices, may be used to produce power locally near the electronic device requiring power (e.g., an electronic component in a wellbore). Conventional bimorph cantilever-type piezoelectric energy harvesters typically have a low transverse bending stiffness. This low transverse bending stiffness can create large stresses in the piezoelectric elements and therefore large power output with small amplitude forces relative to other conventional piezoelectric actuators. However, conventional bimorph cantilever-type piezoelectric energy harvesters tend to be brittle and therefore may have a short lifetime when subject to large deformations.

SUMMARY

[0005] The present disclosure is directed to various embodiments of a flow energy harvesting system configured to generate power. In one embodiment, the flow energy harvesting system includes at least one nozzle-diffuser defining a spline-shaped flow channel, and at least one flow energy harvesting device in the spline-shaped flow channel of the at least one nozzle-diffuser. The spline-shaped flow channel includes a converging portion, a diverging portion, and a constriction section between the converging and diverging portions. The flow energy harvesting device includes a flextensional member having a frame and a cantilever extending outward from the frame. The cantilever is a non-piezoelectric material. The flow energy harvesting device also includes a stack of piezoelectric elements housed in an interior cavity defined in the frame. The frame of the flextensional member is in the converging portion and at least a portion of the cantilever is in the constriction section of the spline-shaped flow channel. The frame is configured to deform and elongate the stack of piezoelectric elements to generate a current based on the piezoelectric effect when a fluid flows through the spline-shaped flow channel and generates unbalanced forces on the cantilever due to aeroelastic flutter

[0006] A resonant frequency of the frame and stack of piezoelectric elements may be less than a resonant frequency of the cantilever. The stack of piezoelectric elements may be isolated from the spline-shaped flow channel. The flow energy harvesting system may also include a pipe. The at least one nozzle-diffuser may include a series of nozzle-diffusers arranged on an outer surface of the pipe, and the at least one flow energy harvesting device may include a series of flow energy harvesting devices in the series of nozzle-diffusers. At least two flow energy harvesting devices of the series of flow energy harvesting devices may be arranged in parallel or in series. The frame and the cantilever of the flextensional member may each be made of metal. The flow energy harvesting system may also include a pair of opposing transverse standoffs extending outward from the frame of the flextensional member. The pair of opposing transverse standoffs fixedly couple the flextensional member of the at least one flow energy harvesting device to the at least one nozzle-diffuser. A length of each of the piezoelectric elements may be parallel to a length of the cantilever of the flextensional member. The length of each of the piezoelectric elements may greater than a thickness of each of the piezoelectric elements.

[0007] The present disclosure is also directed to various method of generating power down hole in a wellbore having a formation wall and a pipe spaced apart from the formation wall by an annular region. In one embodiment, the method includes positioning a flow energy harvesting system in the annular region. The flow energy harvesting system includes a series of nozzle-diffusers defining a series of spline-shaped flow channels, and a series of flow energy harvesting devices in the series of spline-shaped flow channels. Each spline-shaped flow channel includes a converging portion, a diverging portion, and a constriction section between the converging and diverging portions. Each flow energy harvesting device includes a flextensional member having a frame and a cantilever extending outward from the frame. The cantilever includes a non-piezoelectric material. Each flow energy harvesting device also includes a stack of piezoelectric elements housed in an interior cavity defined in the frame. For each of the flow energy harvesting devices, the frame of the flextensional member is in the converging portion of one of the spline-shaped flow channels and at least a portion of the cantilever of the flextensional member is in the constriction section of the spline-shaped flow channel. For each of the flow energy harvesting devices, the frame is configured to deform and elongate the stack of piezoelectric elements to generate a current based on the piezoelectric effect when a fluid flows through the annular region and the plurality of spline-shaped flow channels and generates unbalanced forces on the cantilever due to aeroelastic flutter.

[0008] The method may also include transmitting the current to an electronic device in the wellbore. Positioning the flow energy harvesting system in the annular region may include circumferentially arranging the series of nozzle-diffusers and the series of flow energy harvesting devices in the annular region and orienting the spline-shape flow channels parallel to a longitudinal axis of the wellbore. At least two flow energy harvesting devices of the series of flow energy harvesting devices may be arranged in parallel or in series.

[0009] This summary is provided to introduce a selection of features and concepts of embodiments of the present disclosure that are further described below in the detailed

description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used in limiting the scope of the claimed subject matter. One or more of the described features may be combined with one or more other described features to provide a workable device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] These and other features and advantages of embodiments of the present disclosure will become more apparent by reference to the following detailed description when considered in conjunction with the following drawings. In the drawings, like reference numerals are used throughout the figures to reference like features and components. The figures are not necessarily drawn to scale, nor is every feature in the drawings necessarily required to fall within the scope of the described invention. Additionally, the patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

[0011] FIGS. **1**A-**1**B are a vertical cross-sectional view and a horizontal cross-sectional view, respectively, of a flow energy harvesting device according to one embodiment of the present disclosure in an unloaded state;

[0012] FIGS. **2**A-**2**E depict different degrees of deformation of the embodiment of the flow energy harvesting device illustrated in FIGS. **1**A-**1**B;

[0013] FIGS. **3**A and **3**B are a cutaway perspective view and an enlarged detailed view, respectively, of a flow energy harvesting system according to one embodiment of the present disclosure including a series of nozzle-diffusers and a series of flow energy harvesting devices in the nozzle-diffusers; and

[0014] FIG. **4** is a cross-sectional end view of the embodiment of the flow energy harvesting system illustrated in FIG. **3**A in an annular region of a wellbore configured to generate electricity down hole in the wellbore from fluid flowing through the annular region of the wellbore.

DETAILED DESCRIPTION

[0015] The present disclosure is directed to various embodiments of flow energy harvesting devices and systems including a flextensional member having a frame and a cantilever, and a stack of piezoelectric elements housed in the frame. When a fluid (e.g., a gas or a liquid) flows over the flextensional member, unbalanced forces on the cantilever created by aeroelastic flutter (e.g., unsteady flow forces on the cantilever) generate internal stresses in the cantilever. These internal stresses in the cantilever cause deformation of the frame and the stack of piezoelectric elements in the frame, and the deformation of the piezoelectric elements generates a current according to the piezoelectric effect. According to one or more embodiments of the present disclosure, the flow energy harvesting device is configured such that the length-extensional deformation mode (e.g., the elongation deformation mode) of the piezoelectric elements is excited by unbalanced forces on the cantilever. The length-extensional deformation mode (e.g., the elongation deformation mode) of the piezoelectric elements has an energy conversion efficiency that is greater than the transverse deformation mode of the piezoelectric elements that is employed in conventional bimorph cantilever-type piezoelectric energy harvesters.

[0016] Additionally, according to one or more embodiments of the present disclosure, the resonant frequency of the piezoelectric elements and the frame may be less than the resonant frequency of the cantilever such that the fluid flow does not need to deflect (e.g., bend) the cantilever to deform the piezoelectric elements and generate current. Accordingly, because the cantilever does not need to be sized to bend, the thickness of the cantilever may be increased compared to conventional bimorph cantilever-type piezoelectric harvesters having relatively thin cantilevers to mitigate fatigue and erosion. Additionally, the piezoelectric elements in the frame of the present disclosure are isolated from the fluid flow around the frame of the flextensional member, which is configured to reduce the effects of corrosion, erosion, and overall degradation on the piezoelectric elements which might otherwise reduce the lifecycle of the device.

[0017] The flow energy harvesting devices and systems of the present disclosure may be suitable for use in a variety of energy generation applications, such as, for instance, in the oil industry (e.g., generating power downhole in an oil wellbore to power one or more electric devices in the oil wellbore) and/or in aeronautical and space operations (e.g., generating power from wind or waves on planetary bodies with an atmosphere). By producing power locally near the location of the electronic device requiring power (e.g., sensors and/or actuators), the flow energy harvesting devices and systems of the present disclosure eliminate the need to transmit power over long distances (e.g., down a wellbore), which reduces overall system complexity and the difficulties associated with power transmission.

[0018] With reference now to FIGS. **1**A-**1**B, a flow energy harvesting device **100** according to one embodiment of the present disclosure includes a flextensional member **101** having a frame **102** (e.g., a body or a casing) and a cantilever **103** (e.g., a flextensional actuator) connected to the frame **102**. In one or more embodiments, the cantilever **103** and the frame **102** may be formed separately and subsequently joined together by any suitable manufacturing process or technique, or the cantilever **103** and the frame **102** may be formed integrally as a monolithic member. In the illustrated embodiment, the frame **102** is an elongate body having a pair of opposing ends **104**, **105** (i.e., a leading end **104** and a trailing end **105**) and at least one sidewall **106** (e.g., a cylindrical sidewall) extending between the pair of opposing ends **104**, **105**. In the illustrated embodiment, the cantilever **103** extends outward from the trailing end **105** of the frame **102**. The cantilever **103** includes a fixed end **107** (e.g., clamped end) at the trailing end **105** of the frame **102** and a free end **108** opposite to the fixed end **107**. The cantilever **103** may have any suitable shape, such as, for instance, a flat plate (e.g., a generally rectangular plate or a generally rectangular beam) or a rod. The flow energy harvesting device **100** of the present disclosure also includes a stack of piezoelectric elements **109**, **110** housed in an interior cavity or chamber **111** defined in the frame **102** of the flextensional member **101**. In the illustrated embodiment, the interior cavity **111** of the frame **102** is closed or sealed such that the piezoelectric elements **109**, **110** housed in the frame **102** are isolated from an exterior of the frame **102** (e.g., the piezoelectric elements **109**, **110** housed in the frame **102** isolated from fluid flowing around the frame **102** of the flextensional member **101**). Although in the illustrated embodiment the stack includes a pair of piezoelectric elements **109**, **110**, in one or more embodiments, the stack may include any other suitable number of piezoelectric elements (e.g., more than two piezoelectric elements). In the illustrated embodiment, the cantilever **103** is made from a non-piezoelectric material, such as metal.

[0019] In the illustrated embodiment, the flextensional member **101** also includes a pair of opposing support members **112**, **113** extending into the interior cavity **111** from the opposite ends **104**, **105**, respectively, of the frame **102**. The support members **112**, **113** are configured to support ends of the piezoelectric elements **109**, **110** and maintain the piezoelectric elements **109**, **110** under a compressive load. Additionally, in the illustrated embodiment, the frame **102** of the flextensional member **101** is configured to survive large amplitude vibrations. The maintenance of the piezoelectric elements **109**, **110** under a compressive load and ability of the frame **102** to survive large amplitude vibrations are configured to provide both high energy density in the piezoelectric elements **109**, **110** and fatigue resistance of the flextensional member **101**. In one or more embodiments, the cantilever **103** and the frame **102** of the flextensional member **101** may both be made of metal.

[0020] In the illustrated embodiment, a length of each of the piezoelectric elements **109**, **110** is parallel or substantially parallel to a length of the cantilever **103**. Additionally, in the illustrated embodiment, the length of each of the piezoelectric elements **109**, **110** is greater than a thickness of each of the piezoelectric elements **109**, **110**. When the flow energy harvesting device **100** is in an unloaded state, as shown in FIGS. **1A-1B**, the cantilever **103** extends along an axis that extends between the piezoelectric elements **109**, **110** (e.g., the piezoelectric elements **109**, **110** are mirrored or centered about the axis along which the cantilever **103** extends when the flow energy harvesting device **100** is in an unloaded state). Additionally, in the illustrated embodiment, the piezoelectric elements **109**, **110** are stacked in a direction (e.g., a vertical direction) that is orthogonal or substantially orthogonal to the direction (e.g., a horizontal direction) in which the cantilever **103** extends.

[0021] With continued reference to the embodiment illustrated in FIGS. **1A-1B**, the flextensional member **101** also includes a pair of opposing transverse standoffs **114**, **115**. In the illustrated embodiment, the standoffs **114**, **115** extend outward from the sidewall **106** of the frame **102** of the flextensional member **101**. Although in the illustrated embodiment the flextensional member **101** includes a pair of standoffs **114**, **115**, in one or more embodiments the flextensional member **101** may include any other suitable number of standoffs, such as three or four standoffs arranged around the sidewall **106** of the frame **102**. The standoffs **114**, **115** are configured to fixedly couple the frame **102** of the flextensional member **101** to another structure (e.g., a nozzle-diffuser for directing fluid flow over the frame **102** and the cantilever **103** of the flextensional member **101**).

[0022] When the flow energy harvesting device **100** of the present disclosure is introduced into a fluid flow F (e.g., a gas or liquid flow), the fluid flow F flows along an exterior surface **116** of the frame **102** and over the cantilever **103** of the flextensional member **101**. The fluid flow F may be present in a variety of different environments in which it is desired to locally generate power, such as, for instance, liquid flow in a wellbore or wind or waves on a planetary body with an atmosphere. In one or more embodiments, the flow energy harvesting device **100** may be configured to generate power from any fluid flow F having a flow rate of at least approximately 3 L/min. When an uneven or unsteady fluid F flow flows over the cantilever **103**, differential/unbalanced forces on or along the cantilever **103** create internal stresses in the cantilever **103**. That is, an uneven fluid flow F over the cantilever **103** of the flextensional member **101** may generate aeroelastic flutter (e.g., self-sustained oscillations) at the cantilever **103**, which generates internal stresses in the cantilever **103**. The internal stresses that develop in the cantilever **103** are effectively countered by a point force and a moment at the interface between the fixed end **107** of the cantilever **103** and the trailing end **105** of the frame **102**, which cause deformation of the frame **102** and length-extensional deformation of the stack of piezoelectric elements **109**, **110** in the frame **102**. The length-extensional deformation of the piezoelectric elements **109**, **110** generates a current according to the piezoelectric effect. In the illustrated embodiment, the mechanical advantage between a point force (F_y) on the cantilever **103** and the length-extension load (F_x) on the frame **102** of the flextensional member **101** and the piezoelectric elements **109**, **110** is proportional to L_x/L_y, and the force magnitude on the frame **102** of the flextensional member **101** and the piezoelectric elements **109**, **110** is amplified if $L_y>L_x$.

[0023] FIGS. **2A-2E** depict different degrees of deformation of the frame **102** and the piezoelectric elements **109**, **110** when an unsteady fluid flow F flows over the cantilever **103** of the flextensional member **101** (e.g., when aeroelastic flutter is induced or present at the cantilever **103**). In FIGS. **2A-2E**, the magnitude of the displacement is represented by a color contour, wherein red represents the largest displacement, blue represents the smallest displacement, yellow represents a moderate displacement, and orange represents an intermediate degree of displacement between the displacement levels depicted in yellow and red. The flextensional member **101** is shown in a neutral position (e.g., an undeformed position) in FIG. **2C**. FIGS. **2B** and **2A** depict increasing deformation of the frame **102** in a first direction (e.g., downward) and the resultant increasing elongation (e.g., increasing length-extensional deformation) of the piezoelectric elements **109**, **110** in the frame **102**, and FIGS. **2D** and **2E** depict increasing deformation of the frame **102** in a second direction opposite the first direction (e.g., upward) and the resultant increasing elongation (e.g., increasing length-extensional deformation) of the piezoelectric elements **109**, **110** in the frame **102**.

[0024] In the illustrated embodiment, the resonant frequency of the piezoelectric elements **109**, **110** and the frame **102** of the flextensional member **101** are less than the resonant frequency of the cantilever **103** of the flextensional member **101**. Accordingly, the fluid flow F does not need to deflect (e.g., bend) the cantilever **103** to deform the piezoelectric elements **109**, **110** and thereby generate a current according to the piezoelectric effect. Instead, the fluid flow F may excite the flexural mode of the frame **102** and the piezoelectric elements **109**, **110** without exciting beam deflection of the cantilever **103**. Accordingly, because the cantilever **103** does not need to be sized to enable bending of the cantilever **103**, the thickness of the cantilever **103** may be increased compared to conventional bimorph cantilever-type piezoelectric harvesters having thin cantilevers to mitigate fatigue and erosion of the cantilever **103**.

[0025] In the illustrated embodiment, the piezoelectric elements **109**, **110** housed in the interior cavity **111** of the frame **102** of the flextensional member **101** are isolated from the fluid flow F along the exterior surface **116** of the flextensional member **101**. Isolating the piezoelectric elements **109**, **110** from the fluid flow F is configured to reduce the effects of corrosion, erosion, and overall degradation of the piezoelectric elements **109**, **110** which might otherwise reduce the lifecycle of the flow energy harvesting device **100**.

[0026] With reference now to FIGS. **3A-3B**, a flow energy harvesting system **200** according to one embodiment of the present disclosure includes a series of nozzle-diffusers **201** and a series of flow energy harvesting devices **100**. As described in more detailed below, the nozzle-diffusers **201** are configured to direct a fluid flow over the flow energy harvesting devices **100** to excite the length-extensional deformation mode of the flow energy harvesting devices **100** and thereby generate an electric output via the piezoelectric effect. The flow energy harvesting devices **100** may have any configuration described above with reference to the embodiment illustrated in FIGS. **1A-1B**. In the illustrated embodiment, each of the nozzle-diffusers **201** defines a spline-shaped flow channel **202** having a converging portion **203** (e.g., a nozzle section), a diverging portion **204** (e.g., a diffuser section), and a constriction section **205** between the converging and diverging portions **203**, **204**. Additionally, in the illustrated embodiment, the spline-shaped flow channel **202** includes an inlet **206** upstream of the converging portion **203** and an outlet **207** downstream of the diverging portion **204**.

[0027] The flow energy harvesting devices are arranged in the spline-shaped flow channels **202** of the nozzle-diffusers **201**. In the illustrated embodiment, the frames **102** of the flextensional members **101** are in the converging portions **203** of the flow channels **202** and the cantilevers **103** extend into the constriction sections **205** of the flow channels **202**. Additionally, in the illustrated embodiment, end portions of the cantilevers **103** extend into the diverging portions **204** of the flow channels **202**. The transverse standoffs **114**, **115** on the frames **102** of the flextensional members **101** fixedly couple the frames **102** to portions of the nozzle-diffusers **201** (e.g., to the converging portions **203** of the spline-shaped flow channels **202**).

[0028] In the illustrated embodiment, the series of nozzle-diffusers **201** and the series of flow energy harvesting devices **100** are arranged circumferentially. Together, the circumferentially arranged nozzle-diffusers **201** and energy harvesting devices **100** define an annular band **208**. Flow energy harvesting devices **100** in adjacent circumferential positions on the annular band **208** are arranged in parallel. Additionally, in the illustrated embodiment, each radial position of the annular band **208** includes three nozzle-diffusers **201** arranged in series and three flow energy harvesting devices **100** arranged in series. In one or more embodiments, each radial position of the annular band **208** may include any other suitable number of nozzle-diffusers **201** and a corresponding number of flow energy harvesting devices **100** (e.g., each radial position of the annular band **208** may include a single nozzle-diffuser **201** and a single flow energy harvesting device **100**, a pair of nozzle-diffusers **201** and a pair of corresponding flow energy harvesting devices **100**, or more than three nozzle-diffusers **201** and more than three corresponding flow energy harvesting devices **100**). Accordingly, in the illustrated embodiment, the nozzle-diffusers **201** and the flow energy harvesting devices **100** of the annular band **208** are arranged in both parallel and in series. In one or more embodiments, the nozzle-diffusers **201** and the flow energy harvesting devices **100** may be arranged only in parallel or only in series.

[0029] When the flow energy harvesting system **200** of the present disclosure is introduced into a fluid flow F (e.g., a gas or liquid flow), the fluid flow F first flows into the inlets **206** in the flow channels **202** of the nozzle-diffusers **201** and is then compressed by the converging portions **203** (e.g., the nozzle sections) and the constriction sections **205** of the flow channels **202**. The fluid flow F then expands through the diverging portions **204** (e.g., the diffuser sections) of the flow channels **202** and then exits through the outlets **207**. As the fluid flow F flows through the converging portions **203** of the flow channels **202**, the fluid flow F flows over the frames **102** of the flextensional members **101**. As the fluid flow F flows through the constriction sections **205** of the flow channels **202** and expands through the diverging portions **204** of the flow channels **202**, the fluid flow F flows over the cantilevers **103** of the flextensional members **101**. The fluid flow F through the spline-shaped flow channels **202** tends to produce aeroelastic flutter (e.g., an uneven or unstable flow) at the cantilevers **103** of the flow energy harvesting devices **100**. This unstable flow over the cantilevers **103** creates differential/unbalanced forces and internal stresses in the cantilevers **103**. These internal stresses in the cantilevers **103** cause length-extensional deformation of the frames **102** and the stack of piezoelectric elements **109**, **110** in each of the flextensional members **101**, and the length-extensional deformation of the piezoelectric elements **109**, **110** generates a current according to the piezoelectric effect.

[0030] The length-extensional deformation mode of the piezoelectric elements **109**, **110** has an energy conversion efficiency that is greater (e.g., approximately 3-5 times greater) than a transverse deformation mode of the piezoelectric elements, which is employed in conventional bimorph cantilever-type piezoelectric energy harvesters. In one or more embodiments, one of the flow energy harvesting devices **100** in one of the nozzle-diffusers **201** is configured to generate a power output of approximately 0.18 W at an aeroelastic flutter frequency of the fluid flow F of approximately 300 Hz. In one or more embodiments, one of the flow energy harvesting devices **100** in one of the nozzle-diffusers **201** is configured to generate a power output in the range of hundreds of Milliwatts (e.g., approximately 200 mW to approximately 500 mW). The flow energy harvesting devices **100** of the flow energy harvesting system **200** may be electrically wired together such that the current generated from each of the flow energy harvesting devices **100** may be transmitted into a single electrical line and then transmitted to one or more electronic devices requiring power. In one or more embodiments, the total power produced from the combined flow energy harvesting devices **100** may be from approximately 1 W to approximately 2 W, although in one or more embodiments the total power produced may exceed 2 W by, for example, increasing the number of flow energy harvesting devices **100** in the flow energy harvesting system **200**.

[0031] FIG. **4** depicts the flow energy harvesting system **200** of the present disclosure installed down hole in a wellbore **300** such that the flow energy harvesting system **200** is configured to generate power and supply power to one or more electronic devices down hole in the wellbore **300**. In the illustrated embodiment, the flow energy harvesting system **200** is installed in an annular region **301** defined between a formation wall **302** (e.g., a reservoir rock formation) (or a casing against the formation wall **302**) and a pipe **303** (e.g., completion tubing). When the flow energy harvesting system **200** is installed in the annular region **301** of the wellbore **300**, the spline-shape flow channels **202** are oriented parallel or substantially parallel to a longitudinal axis of the wellbore **300**. When a fluid (e.g., drilling fluid) flows through the annular region **301** and through the flow energy harvesting system **200** (i.e., through the spline-shape flow channels **202** and over the flow energy harvesting devices **100**), the flow energy harvesting devices **100** are configured to generate power via the piezoelectric effect, which may be used to power one or more electronic device in the wellbore **300**. In one or more embodiments, the flow energy harvesting system **200** of the present disclosure may be employed in any other environment in which it is desired to generate power, such as, for instance, in the atmosphere or in a body of water on a planetary body to generate electricity from wind or waves.

[0032] While this invention has been described in detail with particular references to embodiments thereof, the embodiments described herein are not intended to be exhaustive or to limit the scope of the invention to the exact forms disclosed. Persons skilled in the art and technology to which this invention pertains will appreciate that alterations and changes in the described structures and methods of assembly and operation can be practiced without meaningfully departing from the principles, spirit, and scope of this invention. Although relative terms such as "outer," "inner," "upper," "lower," and similar terms have been used herein to describe a spatial relationship of one element to another, it is understood that these terms are intended to encompass different orientations of the various elements and components of the invention in addition to the orientation depicted in the figures. Additionally, as used herein, the term "substantially," "generally," and similar terms are used as terms of approximation and not as terms of degree, and are intended to account for the inherent deviations in measured or calculated values that would be recognized by those of ordinary skill in the art. Furthermore, as used herein, when a component is referred to as being "on" or "coupled to" another component, it can be directly on or attached to the other component or intervening components may be present therebetween. Further, any described feature is optional and may be used in combination with one or more other features to achieve one or more benefits.

What is claimed is:

1. A flow energy harvesting system, comprising:

at least one nozzle-diffuser defining a spline-shaped flow channel, the spline-shaped flow channel comprising a converging portion, a diverging portion, and a constriction section between the converging and diverging portions; and

at least one flow energy harvesting device in the spline-shaped flow channel of the at least one nozzle-diffuser, the at least one flow energy harvesting device comprising:

a flextensional member having a frame and a cantilever extending outward from the frame, the cantilever comprising a non-piezoelectric material; and

a stack of piezoelectric elements housed in an interior cavity defined in the frame,

wherein the frame of the flextensional member is in the converging portion and at least a portion of the cantilever is in the constriction section of the spline-shaped flow channel, and

wherein, the frame is configured to deform and elongate the stack of piezoelectric elements to generate a current based on the piezoelectric effect when a fluid flows through the spline-shaped flow channel and generates unbalanced forces on the cantilever due to aeroelastic flutter.

2. The flow energy harvesting system of claim **1**, wherein a resonant frequency of the frame and stack of piezoelectric elements is less than a resonant frequency of the cantilever.

3. The flow energy harvesting system of claim **1**, wherein the stack of piezoelectric elements is isolated from the spline-shaped flow channel.

4. The flow energy harvesting system of claim **1**, further comprising:

a pipe,

wherein the at least one nozzle-diffuser comprises a plurality of nozzle-diffusers arranged on an outer surface of the pipe, and

wherein the at least one flow energy harvesting device comprises a plurality of flow energy harvesting devices in the plurality of nozzle-diffusers.

5. The flow energy harvesting system of claim **4**, wherein at least two flow energy harvesting devices of the plurality of flow energy harvesting devices are arranged in parallel or in series.

6. The flow energy harvesting system of claim **1**, wherein the frame and the cantilever of the flextensional member each comprise metal.

7. The flow energy harvesting system of claim **1**, further comprising a pair of opposing transverse standoffs extending outward from the frame of the flextensional member, the pair of opposing transverse standoffs fixedly coupling the flextensional member of the at least one flow energy harvesting device to the at least one nozzle-diffuser.

8. The flow energy harvesting system of claim **1**, wherein a length of each of the piezoelectric elements is parallel to a length of the cantilever of the flextensional member.

9. The flow energy harvesting system of claim **8**, wherein the length of each of the piezoelectric elements is greater than a thickness of each of the piezoelectric elements.

10. A flow energy harvesting device comprising:

a flextensional member comprising:

a frame defining an interior cavity; and

a cantilever extending outward from the frame, the cantilever comprising a non-piezoelectric material; and

a stack of piezoelectric elements housed in the interior cavity of the frame.

11. The flow energy harvesting device of claim **10**, wherein a resonant frequency of the frame and the stack of piezoelectric elements is less than a resonant frequency of the cantilever.

12. The flow energy harvesting device of claim **10**, wherein the stack of piezoelectric elements is isolated from an exterior of the frame of the flextensional member.

13. The flow energy harvesting device of claim **10**, wherein the frame and the cantilever of the flextensional member each comprise metal.

14. The flow energy harvesting device of claim **10**, further comprising a pair of opposing transverse standoffs extending outward from the frame of the flextensional member, the pair of opposing transverse standoffs configured to fixedly couple the flextensional member to a structure.

15. The flow energy harvesting device of claim **10**, wherein a length of each of the piezoelectric elements is parallel to a length of the cantilever of the flextensional member.

16. The flow energy harvesting device of claim **15**, wherein the length of each piezoelectric element is greater than a thickness of each piezoelectric element.

17. A method of generating power down hole in a wellbore having a formation wall and a pipe spaced apart from the formation wall by an annular region, the method comprising:

positioning a flow energy harvesting system in the annular region, the flow energy harvesting system comprising:

a plurality of nozzle-diffusers defining a plurality of spline-shaped flow channels, each spline-shaped flow channel comprising a converging portion, a diverging portion, and a constriction section between the converging and diverging portions; and

a plurality of flow energy harvesting devices in the plurality of spline-shaped flow channels, each flow energy harvesting device comprising:

a flextensional member having a frame and a cantilever extending outward from the frame, the cantilever comprising a non-piezoelectric material; and

a stack of piezoelectric elements housed in an interior cavity defined in the frame,

wherein, for each of the plurality of flow energy harvesting devices, the frame of the flextensional member is in the converging portion of one of the spline-shaped flow channels and at least a portion of the cantilever of the flextensional member is in the constriction section of the one of the spline-shaped flow channels, and

wherein, for each of the plurality of flow energy harvesting devices, the frame is configured to deform and elongate the stack of piezoelectric elements to generate a current based on the piezoelectric effect when a fluid flows through the annular region and the plurality of spline-shaped flow channels and generates unbalanced forces on the cantilever due to aeroelastic flutter.

18. The method of claim **17**, further comprising transmitting the current to an electronic device in the wellbore.

19. The method of claim **17**, wherein the positioning of the flow energy harvesting system in the annular region comprises circumferentially arranging the plurality of nozzle-diffusers and the plurality of flow energy harvesting devices in the annular region and orienting the spline-shape flow channels parallel to a longitudinal axis of the wellbore.

20. The method of claim **17**, wherein at least two flow energy harvesting devices of the plurality of flow energy harvesting devices are arranged in parallel or in series.

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